

# ELECTROHYDRODYNAMIC POOL BOILING IN REDUCED GRAVITY

Principal Investigator: B. D. Shaw

Graduate Student: S. L. Stahl

Mechanical and Aeronautical Engineering Department  
University of California  
Davis, CA 95616-5294

## ABSTRACT

This research is concerned with studying the effects of applied electric fields on pool boiling in a reduced-gravity environment. Experiments are conducted at the NASA Lewis 2.2 sec Drop tower using a drop rig constructed at UC Davis. In the experiments, a platinum wire is heated while immersed in saturated liquid refrigerants (FC-72 and FC-87), or water, causing vapor formation at the wire surface. Electric fields are applied between the wire surface and an outer screen electrode that surrounds the wire. Preliminary normal-gravity experiments with water have demonstrated that applied electric fields generated by the rig electronics can influence boiling characteristics. Reduced-gravity experiments will be performed in the summer of 1996. The experiments will provide fundamental data on electric field strengths required to disrupt film boiling (for various wire heat generation input rates) in reduced gravity for a cylindrical geometry. The experiments should also shed light on the roles of characteristic bubble generation times and charge relaxation times in determining the effects of electric fields on pool boiling. Normal-gravity comparison experiments will also be performed.

## INTRODUCTION

Pool boiling heat transfer is important in a number of applications. There are several different regimes in pool boiling, e.g. nucleate boiling and film boiling [1]. Nucleate boiling is characterized by formation of individual bubbles at a heated surface. The bubbles leave the surface, allowing fresh liquid to come into contact with the surface. This fresh liquid forms more bubbles, and the cycle repeatedly occurs, promoting high heat transfer rates. It has been observed, however, that critical surface heat fluxes ( $q''_{\max}$ ) can exist such that nucleate boiling can no longer be sustained, leading to the formation of a layer of vapor which remains deposited on the heat transfer surface; this corresponds to the film boiling regime [1]. Heat transfer coefficients are generally much lower in the film boiling regime than for nucleate pool boiling, and surface temperatures are typically substantially higher. With pool boiling heat transfer, it is generally desirable to operate in the nucleate boiling regime so that: (i) high heat transfer coefficients, and therefore small heat transfer surface areas, may be realized; and (ii) acceptably-low surface temperatures may be attained (e.g., for safety reasons). As a result, it is important to be able to predict  $q''_{\max}$ .

Theory and experiment suggest that gravity, when it is the only body force present, plays an important role in determining  $q''_{\max}$ . Theoretically, it is predicted [1] that the critical heat flux scales with the gravitational acceleration raised to the one-fourth power (i.e.,  $q''_{\max} \sim g^{1/4}$ , where "g" is the gravitational acceleration). Experimental data [2] tend to support this scaling with gravity. Physically, as g decreases, buoyancy forces become less effective at removing bubbles from surfaces. Hence, in reduced gravity the critical heat flux  $q''_{\max}$  may be substantially

decreased. This results in a penalty of larger heat transfer areas to safely transfer a given amount of heat. In space-based systems, as well as earth-based systems, there are substantial cost and size advantages to be gained by increasing  $q''_{\max}$ . It is thus desirable to study ways of enhancing boiling heat transfer so that  $q''_{\max}$  may be increased.

One method for increasing  $q''_{\max}$  involves applying electric fields in the region where bubble nucleation and growth (boiling) occurs. Nucleate boiling in the presence of electric fields has been the subject of numerous studies. Electric fields have been shown (in 1-g) to be capable of increasing  $q''_{\max}$  in a controllable manner by an order of magnitude or more. A 1978 review of the subject may be found in Ref. [3]. More recent studies have also been reported [4-9] (though no reduced-gravity data has been found). Ground-based studies have shown that electric fields can substantially increase  $q''_{\max}$ , basically by causing film boiling to become unstable and by strongly affecting bubble motions. Vapor blankets associated with film boiling are destabilized by sufficiently-strong electric fields, thus promoting nucleate boiling at high heat fluxes.

Electric fields influence bubble and liquid behaviors in several ways. For example, convective flows are induced in liquids by electric fields; these flows tend to increase heat transfer rates, and may actually delay the onset of nucleate boiling. Effects of electric fields on bubbles can be dramatic, splitting larger bubbles into smaller ones and inducing significant bubble velocities through the action of electrical forces [4,5]. The time  $t_c = \epsilon/\sigma_e$ , where  $\epsilon$  is liquid dielectric permittivity and  $\sigma_e$  liquid electrical conductivity, is a characteristic time for charge relaxation (accumulation) to occur around a bubble under the action of an applied electric field. The magnitude of  $t_c$  has been shown to be important in determining pool boiling behavior [5,6]. Physically, it seems reasonable that if  $t_c$  is small relative to a characteristic time  $t_{res}$  for bubble residence time in the electric field zone, electric fields may significantly affect bubble behaviors. Conversely, if  $t_c \gg t_{res}$ , electric fields may not be significant. Such phenomena have been noted in 1-g experiments with R-11 ( $\text{CCl}_3\text{F}$ ) [9]. In these experiments,  $t_{res}$  may have been strongly influenced by buoyancy forces.

In reduced gravity, buoyant residence times may become quite large, suggesting that electric field effects may be significant for liquids with large values of  $t_c$ . It is noted, however, that 1-g experiments have suggested that the characteristic bubble generation time  $t_b$  (i.e., the time to generate a bubble at the surface) is also important [4,5]; electric field effects (e.g., on  $q''_{\max}$ , heat transfer coefficients, and bubble behaviors) were strong when  $t_c \ll t_b$ , and weak when  $t_c \gg t_b$  (it was also shown that varying the electric field magnitudes allowed control of heat transfer [4,5]). These works, however, did not take buoyant residence times into account. It seems plausible that electric field effects should be important if  $t_c \ll t_{res}$ , regardless of whether  $t_c \gg t_b$  or  $t_c \ll t_b$ , that is, so long as the residence time is sufficient for electric effects to occur. Reduced-gravity experiments (which will greatly increase  $t_{res}$ ) with liquids that have  $t_c \gg t_b$  or  $t_c \ll t_b$ , should thus delineate whether  $t_b$  or  $t_{res}$  is more important in determining the effects of electric fields.

Available theory suggests that  $q''_{\max}$  should scale linearly with applied electric field magnitudes when gravity is negligible [8]. It is noted, however, that this theory assumes liquids are perfect conductors, the film exists over a flat plate, and uniform DC fields are present. Any or all of these assumptions may be violated in an application. Many refrigerants, e.g. fluorocarbons, have very low electrical conductivities.

## SCIENTIFIC OBJECTIVES

This research is focused upon investigating the effects of electric fields on reduced-gravity pool boiling. The following areas are addressed:

It is expected that it will be shown that electric fields will significantly (and controllably) increase reduced-gravity nucleate boiling heat transfer rates and maximum heat fluxes for the cylindrical geometry considered.

It will be investigated whether available theory will predict  $q''_{\max}$  (critical heat fluxes) when electric fields are applied in reduced gravity.

It will be investigated whether bubble dynamics will be significantly affected by electric fields. It is expected that electric fields will produce smaller bubbles, and will strongly affect their motions, as observed in 1-g experiments. Contrary to 1-g experiments, these trends are expected to apply as long as  $t_c \gg t_{\text{res}}$ , regardless of whether  $t_c \gg t_b$  or  $t_c \ll t_b$ .

## SCIENTIFIC AND TECHNICAL SIGNIFICANCE

Scientifically, this research will advance knowledge of the effects of electric fields on boiling heat transfer. Reduced-gravity studies will decrease buoyancy forces to negligible levels, allowing investigation of the relative importances of liquid charge relaxation times ( $t_c$ ) and characteristic bubble production times ( $t_b$ ), both of which are considered to be of fundamental importance. Physically, it seems reasonable to expect that a bubble must be exposed to an electric field for at least the time  $t_c$  for the field to affect the bubble. Normal-gravity studies have suggested that electric field effects are strongest when  $t_c \ll t_b$  and weak when  $t_c \gg t_b$ . However, buoyant bubble residence times ( $t_{\text{res}}$ ) were generally small relative to  $t_c$  when the  $t_c \gg t_b$  studies were performed, suggesting that buoyancy may have played a critical role. It seems likely that electric field effects will be important if  $t_c$  is small relative to bubble residence times in the electric field zone, regardless of whether  $t_c \ll t_b$  or  $t_c \gg t_b$ . Reduced-gravity experiments will be performed with liquids for which  $t_c \ll t_b$  or  $t_c \gg t_b$ . The experiments will render buoyant residence times large relative to  $t_c$ , and will allow this hypothesis to be evaluated. In addition, quantitative data will be obtained on the effects of electric fields on heat transfer coefficients and critical heat fluxes in reduced-gravity.

Technically, this research will help in the development of pool boiling heat transfer devices for use in space as well in terrestrial applications. A major obstacle to utilizing pool boiling in space is the fact that the critical heat flux decreases with decreasing gravity levels. Electric fields may act as a substitute for gravity, increasing critical heat fluxes and boiling heat transfer rates in controllable manners. This may help to lead to space-based (and earth-based) applications of this technology. Space applications are especially significant, in view of the possible weight savings involved; small reductions in weight generally lead to substantial cost savings associated with putting a system in orbit.

## RESEARCH APPROACH

A pool boiling apparatus has been constructed at UC Davis for use in the 2.2 sec drop tower at the NASA Lewis Research Center (see Fig. 1 for a schematic). Liquids at saturation conditions (at one atm) will be studied. This apparatus consists of a chamber initially filled with liquid. Inside the chamber is a circular platinum wire ( $\approx 0.1$  mm diameter and 70 mm in length) surrounded by a concentric screen about 70 mm in length and 10 - 30 mm in diameter (variable). Boiling is caused to occur by passing electrical current from a DC-DC convertor through the wire. Measurements of wire voltage drop and current allow the average wire resistance to be calculated. Since wire resistance is a known function of temperature, the average wire temperature can thus be

calculated; because the wire is thin, wire temperature gradients should be small (these gradients will be estimated). The average surface heat flux  $q''_s$  will also be easily calculated from knowledge of the platinum wire voltage drop and current.

The platinum wire and outer concentric screen is connected to an on-board high voltage power supply (a DC-DC convertor). If cylindrical symmetry is assumed, the electric field  $E$  between the screen and the platinum wire is approximately given by  $E = (V/r)/\ln(r_2/r_1)$ , where  $V$  is the voltage difference between the wire and screen,  $r$  the radial coordinate, and  $r_1$  and  $r_2$  denote the wire and screen radii, respectively. For  $V = 1$  kV (attainable with the DC-DC convertors used),  $r_1 = 0.05$  mm and  $r_2 = 5$  mm,  $E \approx 4$  MV/m near the wire. These field strengths significantly increase boiling rates and  $q''_{\max}$  in 1-g conditions [3-6,8,9].

For pressure control, a balloon has been mounted inside the chamber such that one side of the balloon is exposed to the test liquid while the other side is open to the atmosphere (see Fig. 2 for a schematic). The balloon simply collapses as bubbling ensues, maintaining the test-cell volume very closely to local atmospheric pressure. A thermal control system to maintain the bulk fluid at saturation conditions has also been implemented.

Some drop tower experiments will proceed by stabilizing boiling for a few seconds in 1-g at the top of the drop tower, before the drop occurs. The package will then be dropped, providing the reduced-gravity environment. Other experiments will involve initiating boiling while in  $\mu g$ . The experiment package is computer-controlled while in reduced gravity. Platinum wire currents and voltages are continuously monitored and recorded with an on-board data acquisition system. The high voltage applied between the wire and the screen is monitored and recorded, as is the DC-DC convertor current. Three thermistors are used for liquid temperature measurements, and a pressure transducer is used for test-cell pressure measurements; the temperature and pressure of the liquid are recorded by an on-board data acquisition system. After each drop, data will be downloaded to a computer for later analysis. On-board video cameras, orthogonally aligned, provide visual records of the experiments. One camera shows a close-up of the platinum wire, while the other provides a wider field of view showing the wire as well as the screen. Details of bubble nucleation and growth, as well as bubble behavior after detachment will be observed.

Experiment procedures will involve setting  $q''_s$  and  $V$  to specific values. Data will be evaluated to determine if a transition to film boiling occurs during a drop or whether existing film boiling can be disrupted in  $\mu g$  after the electric field is activated. The parameters  $q''_s$  and  $V$  will be systematically varied from drop to drop so that  $q''_{\max}$  and wire heat transfer coefficients may be determined as a function of the applied voltage. For comparison, the same experiments will be performed in 1-g using the same apparatus. This should shed light on the effects of gravity on boiling phenomena, for example characteristic bubble sizes and heat transfer rates.

## RESULTS TO DATE

Preliminary experiments in normal gravity (using water) have shown that the drop rig is functional. These experiments have demonstrated that electric fields applied by the drop rig circuitry can influence boiling heat transfer in normal gravity. Figure 3 shows experimental values of wall heat fluxes vs. wall superheat with and without electric fields. In each case, the wire diameter was 125  $\mu m$  and the screen electrode diameter was 20 mm in diameter (both were about 70 mm in length). As is evident in these figures, applied electric fields increased heat transfer rates. These preliminary experiments utilized voltage gradients of about 1 kV/cm in the vicinity of the wire; future experiments in both normal gravity and reduced gravity will involve voltage gradients that will be up to about 10 times larger. In addition, the screen diameters will be varied in order to assess effects on finite-length wires and screen electrodes.

## RESEARCH PLAN

The next phase of the work will involve performing reduced-gravity experiments at the NASA Lewis Research Center during the summer of 1996. Following this, comparison experiments in normal gravity will be performed at UC Davis using the same apparatus.

## ACKNOWLEDGEMENTS

The contributions of R. Brodeur, T. Brodeur, R. Kapesser, T. Ferrel, A. Jenkins, N. Smith, J.-B. Wei, G. Wilson, and the UCD Engineering Shop Personnel in helping to design and construct the apparatus are gratefully acknowledged. Technical supervision was provided by Dr. F. Chiaramonte of the NASA Lewis Research Center.

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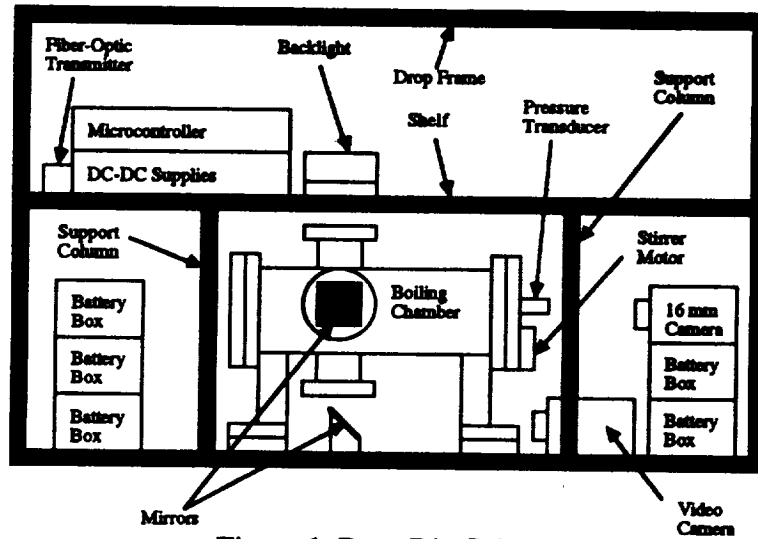


Figure 1. Drop Rig Schematic

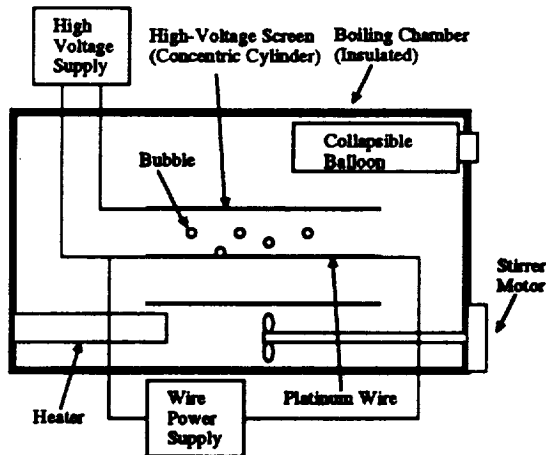


Figure 2. Boiling chamber schematic.

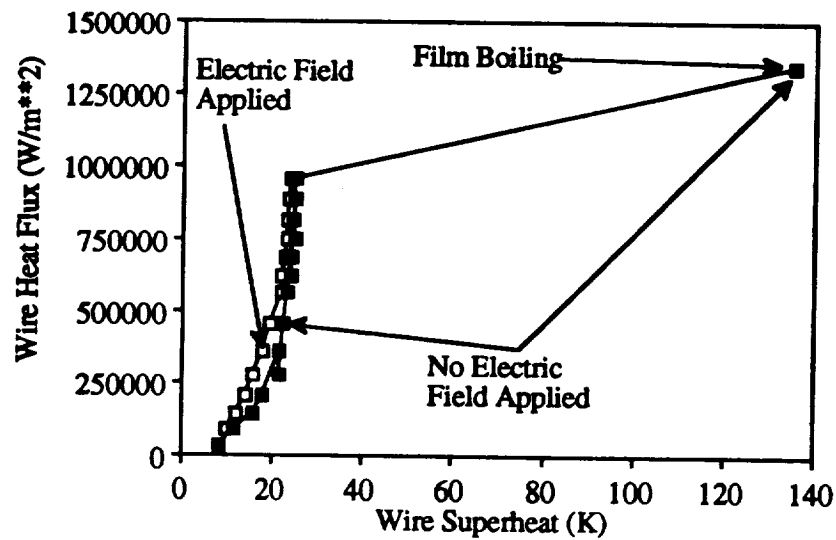


Figure 3. Heat flux from the wire surface for boiling in water (normal gravity).